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ABSTRACT

The drag coefficients for cylinders normal to the flow have been determined experimentally at Mach ~ 2, Mach ~ 4, and Mach ~ 6 with Knudsen numbers extending from continuum conditions to free molecule flow conditions. The results indicate a smooth transition from inviscid values at low Knudsen numbers to free molecule flow predictions for diffuse reflections at high Knudsen number. Small departure theories which are applicable to the "near free molecule flow" regime are compared to the experimental data.

I. INTRODUCTION

One of the central problems of rarefied gas dynamics is to understand the transition from free molecule flow at extremely low density to continuum flow at high density. For internal flow situations, e.g., between parallel plates or concentric cylinders, along ducts or through orifices, there is a reasonably extensive body of theoretical and experimental information.[1] Theoretical approaches of two general types have been made: (i) "over-all" theories, seeking to obtain solutions of the Boltzmann equation, or approximations to it, for arbitrary gas density, and (ii) "small departure" theories, in which only the initial deviations from the limiting cases of continuum and free molecule flow are sought; these are usually referred to as slip flow and near free molecule flow, respectively. Where relevant, the available experimental results for such internal flows seem to be in reasonable accord with the theoretical predictions -- although it is perhaps well to temper this remark with the realization that most of these comparisons have so far been confined to situations which constitute relatively uncritical tests of theory.

For external flows of aerodynamic interest, information is much less extensive. No over-all solutions have been proposed, so that experimental results of an over-all nature are particularly desirable. Experiments of this type have been carried out for sphere drag at very low[2] and at very high[3] Mach number, and for the heat transfer characteristics of cylinders at intermediate Mach numbers.[4-7] The present experiments seek to provide additional experimental data of this type in the form of cylinder drag at intermediate Mach numbers. "Small departure" theoretical results of some relevance to this case are available in the near free molecule flow range, and it has been possible to make at least a tentative comparison between theory and experiment. For the high density condition, on the other hand, the theoretical problem is much more complicated and has so far not been carried out -- even for the limiting case of continuum flow -- so that no comparison between experiment and theory has been possible.

II. EXPERIMENTAL METHOD

A. Experimental Equipment

All tests were performed at the Aeronautical Sciences Laboratory located at the Richmond Field Station of the University of California. The Number 4 low density wind tunnel and its associated standard instrumentation[8] was used to obtain continuous, stable, unheated supersonic flow at static pressure levels from 60 to 200 microns Hg. Three fixed axisymmetric nozzles were employed; a $M \sim 2$ nozzle,[9] a $M \sim 4$ nozzle,[10] and a $M \sim 6$ nozzle.[8]

Axial forces acting on the models were measured with a null type one component beam balance.[11] A linear variable differential transformer was used to sense the null position of the beam and model. The moment created by the combination of sting length and the aerodynamic force acting on the model is opposed by a spring force applied to the beam a fixed distance from the crossed strip flexure pivot. A moment summation about the pivot center thus provides a measure of the aerodynamic force. Figure 1 presents a schematic drawing of the balance system, while Figure 2 displays the balance in operation in the wind tunnel.

Five separate models were designed for these tests. Three were constructed as butt welded iron-constantan thermocouples with diameters of 0.010 inch, 0.0033 inch and 0.0015 inch. Tests involving these larger models permitted the simultaneous measurement of model temperature during the run. Two smaller models of tungsten, 0.0009 inch diameter and 0.0003 inch diameter were also used. Electrical contact with the thermocouple models when mounted in the balance was accomplished by means of two mercury pools located on the upper plate of the balance. Care was taken to insure against extraneous forces due to contact of the wire model and the pool walls.

A combination of two adjustable length radial shields connected to a fixed circumferential shield isolated the mounting yoke and the model leads from the stream and from random wind currents outside of the uniform core flow. The radial shields were terminated by slotted caps which provided a close fit about the model. Previous work[12] has revealed the need to prevent a radial flow of air within the shield. Although both tapered and square ended shields were investigated, only square ended shields were used in the final tests.

B. Experimental Procedures

The data obtained in these tests can best be considered in two separate categories. The first involves those pressure and temperature measurements necessary to the control and identification of the flow conditions, while the second category contains those measurements which determine the magnitude of the aerodynamic forces.

During a given run several pressure measurements are made to establish and monitor the flow conditions. The upstream stagnation condition is first established by the flow control system and the magnitude of the pressure observed with either an oil manometer when less than 20 mm Hg, or a mercury manometer for all stagnation pressures above this value. The impact pressure is next measured using an 0.300 inch diameter source-shaped probe located so that the tip of the probe is approximately one half inch upstream of the model. With the probe in this position, the nozzle wall pressure and the test chamber pressure as measured at the exit plane of the nozzle are compared and brought into agreement to insure a balanced jet exit condition. The means of achieving such a balance is either by adjustment of an iris type downstream diaphragm or by bleeding atmospheric air into the downstream chamber. After a balanced exit condition has been achieved the impact pressure is observed with the oil manometer. The upstream air temperature is determined by a mercury in glass thermometer. With the flow conditions thus established the impact probe is removed from the stream and the force measurement can be made.

The determination of an aerodynamic force acting on a model requires a number of measurements prior to the actual test and only two measurements during the run period; these latter data are the extension of the quartz spring and the length of exposed model and its location relative to the balance pivot center. A micrometer screw-nut-counter arrangement is used to display the spring extension while the model length and location are directly observed with a cathetometer. The basic dimensions of the balance beam, vertical sting and model diameter are all determined prior to the run, together with the calibration of the quartz spring.

To minimize tunnel running and model setup time the sequence of runs was scheduled as follows. For one model and nozzle combination at least four runs were made with each run characterized by a given length of exposed model. Each run contained measurements of the aerodynamic force for four separate flow conditions. Repetition of a run would then involve opening the wind tunnel, changing the radial shields to expose a new model length, closing the tunnel, pumping down and repeating the same flow settings and force measurements. Such a series of runs would thus provide sufficient data to determine four axial force coefficients for a limited range of Knudsen number. While the model was in the balance, a new nozzle would be inserted into the wind tunnel and data obtained in a like manner for different Mach and Reynolds number conditions.

After all three nozzles were used, the entire operation was repeated with a new model diameter. Approximately one hundred runs were required for this investigation.

III. DATA REDUCTION AND ERROR ANALYSIS

A. Procedure

The free stream flow properties were based on the measurement of the upstream stagnation pressure and temperature and the impact pressure in the test section. Conventional flow tables[13] were used to determine the free stream pressure, temperature, Mach number and dynamic pressure. Free stream Reynolds numbers were calculated on the basis of the air viscosity as given by Bromley and Wilke.[14]

The aerodynamic force acting on a model with a given exposed length was computed by a simple moment summation about the balance pivot axis. No attempt was made to predict the magnitude of or to correct for end effects due to flow interference near the shields. The model lengths exposed to the stream varied from approximately two inches down to three eighths of an inch, permitting the assumption that the end effects could be neglected. For the same set of flow conditions and model size, the force data were presented in a plot of force vs. model length, as shown in Figure 3. The extrapolation of these results to zero length indicates a minor possible end effect. It is interesting to note that the force intercept was consistently at a negative value for those runs with a high free stream Reynolds number, while low Reynolds number flows produced a slightly positive intercept. The positive intercept is consistent with the results of Sreekanth[15], although the deviation from the origin is much less for the present data.

The value of dF/dL for each model and flow condition was then used to determine the drag coefficient, C_x. These results are presented as a function of the Knudsen number k_D, based on the model diameter, in Figures 4, 5, and 6 for the three Mach conditions investigated.

The model temperature data as determined by the thermocouple models together with the free stream properties were used to determine the limiting drag coefficient as based on free-molecule flow theory. A typical curve of the measured temperature ratio vs. Knudsen number is shown in Figure 7. Although a true asymptotic value was not determined with the 0.0015 inch model, a minor extrapolation appears warranted.

A final presentation of results is found in Figure 8, where the ratio of the measured drag coefficient to the limiting drag coefficient for a given Mach number is plotted as a function of $1/k_D$.

B. Error Analysis

The determination of the force coefficient and the Knudsen number in this program involved a large number of measurements, each contributing a source of error. A convenient, conservative and simple, yet adequate method of determining the maximum error possible in such an investigation can be carried out with the assumption that all errors are additive, in phase, and are based on known flow irregularities and on the least count of the individual instruments. A detailed summary of such an evaluation is given by Maslach and Talbot.[16]

For this investigation the three main sources of error were: (1) the determination of the dynamic pressure, (2) the determination of model diameter, and (3) the limited spring extension necessary to balance the minute aerodynamic forces acting on the smallest models. Fortunately axial flow irregularities in the flow field are negligible for the model dimensions used in this investigation. An indication of the value of dq_∞/q_∞ is given in Table I for all three nozzles.

Model diameters were determined by the use of an Electrolimit gage except for the two smallest models where the Sigmund Cohn values based on a weight per unit length procedure was used to compute the diameter. The tungsten wires were produced by an etching process from rods of known density and the final diameter was observed with a conventional toolmakers microscope and found to be extremely uniform. The error contribution d(AC)/(AC) is based on the raw data and represents the best choice of spring strength necessary to accommodate all forces to be measured in one run. Miscellaneous small error contributions which originate in the measurement of sting, beam, and model length, and spring calibrations are also indicated.

Mach	1.96	4.00	5.92
dq_∞/q_∞	0.7%	0.4%	0.4%
d Dm/Dm			
Largest Model	0.6%	0.6%	0.6%
Smallest Model	1.5%	1.5%	1.5%
d(AC)/(AC)			
Largest Model	0.5%	0.4%	0.2%
Smallest Model	1.6%	0.8%	0.5%
Other Sources	0.7%	0.7%	0.7%
Total			
Largest Model	2.5%	2.1%	1.9%
Smallest Model	4.5%	3.4%	3.1%

TABLE I

ERROR SOURCES AND CONTRIBUTIONS

IV. DISCUSSION

A. The Viscous Region

There is, of course, no solution of the Boltzmann equation for arbitrary density for the supersonic flow past a cylinder. The inviscid continuum value of the drag coefficient C_D, corresponding to the limit as the Knudsen number $K \to 0$, has been established empirically by numerous experiments in normal density wind tunnels. Since all transport phenomena become unimportant in this limit, C_D is a function of the Mach number M only. For small but increasing values of K viscous effects begin to be of importance. In the boundary layer range, the drag force is affected by a complex combination of skin friction, displacement pressure and separation-base-pressure phenomena. C_D then depends on the Reynolds number Re and the stream and surface temperatures T_∞ and T_w as well as the Mach number, since these parameters all affect the boundary layer characteristics (the present discussion is confined to the case of air, so that the specific heats and the transport coefficients of viscosity and thermal conductivity are all fixed by the other quantities). In the laminar boundary layer range C_D is expected[17] to have the form $C_D \sim C_D(K=0) + f(M,T_w,T_\infty)/\sqrt{Re}$, or, equivalently, $C_D \sim C_D(K=0) + g(M,T_w,T_\infty)\sqrt{K}$, since $K \sim M/Re$. However, the quantities f and g have not been determined theoretically. For slightly higher values of K, the flow phenomena become even more complex. Vorticity, interaction, curvature and slip effects are all known to affect the boundary layer in the forward stagnation region. Presumably they will also affect the separation point and the base pressure. It is also possible that the flow is not steady, so that the measured drag force is actually an average value. The emphasis of the present experiments was not on the determination of these various viscous effects, and, in the absence of any relevant theory, it has not seemed particularly useful to subject the comparatively limited data to empirical analysis. Referring to

Figures 4, 5, and 6, it should be noted, however, that: (1) the measurements tend very smoothly to the proper inviscid values[18] as $K \rightarrow 0$, (2) the indicated dependence of C_D on K is limited to a particular set of values of the other relevant parameters, such as T_w, T_∞ and the slip coefficients -- even for relatively small K.

B. Free Molecule Flow

Turning next to the other extreme of high Knudsen number, somewhat more definite conclusions can be reached. For $K \rightarrow \infty$ the free molecule flow conditions are expected to be satisfied, according to which inter-molecular collisions are of negligible importance. The drag coefficient now depends on the free stream Mach number, on the cylinder surface temperature, and upon the nature of the interaction of the incident molecules with the surface. This latter is not known directly, but from many molecular beam and similar surface interaction studies, it is to be expected that the reemitted flux of air molecules from the surface of the cylinder models of these tests, which are relatively rough and covered with a layer of adsorbed gas, should be very nearly in complete Maxwellian equilibrium with the surface. We term such interaction "diffuse" for purposes of brevity. Making this assumption, the drag coefficient can be calculated[1] as

$$D_{D,\infty} = \frac{\sqrt{\pi}}{S} e^{-S^2/2} \left[(S^2 + \frac{3}{2}) I_o \frac{S^2}{2} + (S^2 + \frac{1}{2}) I_1 \frac{S^2}{2} \right] + \frac{\pi^{3/2}}{4 S_w} \qquad (4.1)$$

(diffuse reflection)

where S is the molecular speed ratio,

$$S = U/\sqrt{2RT_2} = \sqrt{\gamma/2}\; M \qquad (4.2)$$

and $S_w = U/\sqrt{2RT_w}$. The dependence of $C_{D,\infty}$ on the surface temperature T_w

will be noted. For the present conditions this is an important contribution. The theoretical values indicated on the graphs and elsewhere have been determined by using the values of T_w obtained during this investigation. The effect on $C_{D,\infty}$ of a departure from Maxwellian equilibrium for the reemitted flux can be calculated in terms of empirical surface interaction parameters which have been defined in such a way as to correspond more or less to a measure of the departure from such diffuse surface interaction. In principle, the present experiments could provide the basis for the determination of these empirical parameters. However, the drag coefficient is very insensitive to these parameters for the present range of flow conditions and surface temperature, particularly for the higher values of M. As an indication of this, the hypothetical extreme of specular reflection, corresponding to no interaction at all between the surface and the incident molecules, leads to a theoretical drag coefficient of the form[1]

$$C_{D,\infty} = \frac{4\sqrt{\pi}}{3S} \, e^{-S^2/2} \left[(S^2 + \frac{3}{2}) I_o \frac{S^2}{2} + (S^2 + \frac{1}{2}) I_1 \frac{S^2}{2} \right] \qquad (4.3)$$

(specular reflection)

This differs from the value for diffuse reflection by only 3-10% in the present range of conditions. Inspection of the data confirms the expected agreement with the value corresponding to diffuse reflection, but it must be recognized that the absolute accuracy is not adequate to provide a basis for the inference of precise values for the empirical surface interaction parameters. It is probably well to recall also that there is no a priori assurance that the actual surface interaction will give rise to a drag somewhere in the region bracketed by the "diffuse" and "specular" values[19]-- particularly for the case $T_w \ll T_o$. For the present case of $T_w \sim T_o$, however, the interaction would have to be quite anomolous to give rise to a drag force outside this bracket.

C. Near Free Molecule Flow

Of perhaps even more interest than the free molecule flow limit for $K \to \infty$ is the so-called "near free molecule flow" region of large but finite K. A number of theoretical calculations of interest in this range have been carried out recently. The cylinder has not been investigated, so that a direct comparison between theory and experiment is not possible. The most nearly relevant investigations are those of Baker and Charwat[20] and of Willis.[21] They have both considered the case of a two-dimensional strip oriented perpendicular to the flow, and both have assumed diffuse reemission from the surface.

Baker and Charwat have limited their results to the case of $S \to \infty$, although they include the effects of finite S_w. They idealize the gas as consisting of hard sphere molecules and estimate the effect on the drag of various types of collisions between incident and reemitted molecules. Their result for the drag coefficient of the strip is given in the form

$$C_D = 2 + \frac{4}{3}\frac{V_e}{V_o} - (.32 + 1.36\frac{V_e}{V_o})\ B, \qquad (4.4)$$

where V_e and V_o are the reemission and free stream velocities. B is given by

$$B = \frac{2a}{\lambda_\infty} \cdot \frac{|\bar{W}|}{\sqrt{2}\,V_e} = \frac{1}{K}\ \frac{|\bar{W}|}{\sqrt{2}\,V_e} \ . \qquad (4.5)$$

$$K = \lambda_\infty / d \qquad (4.6)$$

where a is the strip half width $(2a = d)$, λ_∞ is the free stream near free path and $|\bar{W}|$ is the mean relative speed of free stream molecules with respect to reemitted molecules. We take $|\bar{W}| = V_o + V_e$, which is a slight over-estimation.

The quantity V_e/V_o is related to the reemission speed ratio $S_w = U/\sqrt{2RT_w}$ as follows: the term $2 + \frac{4}{3}\frac{V_e}{V_o}$ is identified as the free molecule flow value ($B = 0$) for the drag coefficient of the strip. For $S, M \rightarrow \infty$, this is known to be $2 + \sqrt{\pi}/S_w$. Hence, it is appropriate to set

$$\frac{4}{3}\frac{V_e}{V_o} = \frac{\sqrt{\pi}}{S_w} . \tag{4.7}$$

For purposes of comparison with the experiments, the free molecule flow value for the strip with $M, S \rightarrow \infty$ is replaced by $C_{D,\infty}$, the proper expression for the cylinder at the appropriate values of S and S_w, as indicated in Equation (4.1).

Hence, we obtain

$$C_D = C_{D,\infty} - F(S_w)/K \tag{4.8}$$

where

$$F(S_w) = 1.19 + 1.28/S_w + 0.170\, S_w . \tag{4.9}$$

Willis has treated the problem in terms of the Krook model equation, rather than the Boltzmann equation, for finite S and S_w, and also in terms of the Boltzmann equation for the limiting case $S \rightarrow \infty$, $S_w \geq 2$. He uses an iteration process, the first term of which corresponds to the near free molecule flow correction. The collision frequency in the model equation is adjusted so as to give agreement between the two results for the case $S \rightarrow \infty$. His results require a numerical integration and are presented in Figures 21 and 22 (revised) of Reference 22 in the form of certain plots of two functions, the "number flux" function δN^* and the "drag" function δD^* vs. the parameters S and S_w. They can be put in the form

$$C_D = C_{D,o} - G(S,S_w) \ln K/K \qquad (4.10)$$

where

$$G(S,S_w) = 0.66\, S_w \left\{ \frac{p_{i,o}}{\frac{1}{2}\rho U^2}\, \delta D^* + \frac{p_{r,o}}{\frac{1}{2}\rho U^2}\, \delta N^* \right\} \qquad (4.11)$$

The quantities $p_{i,o}$ and $p_{r,o}$ are the incident and reemitted normal momentum fluxes (pressures) for the free molecule flow case (diffuse reflection), namely,[1]

$$p_{i,o} = \frac{1}{2}\rho U^2 \left\{ 1 + \operatorname{erf} S + \frac{S\, e^{-S^2} + \frac{\sqrt{\pi}}{2}(1 + \operatorname{erf} S)}{\sqrt{\pi}\, S^2} \right\} \qquad (4.12)$$

$$p_{r,o} = \frac{1}{2}\rho U^2 \cdot \frac{\sqrt{\pi}}{S_w} \left\{ \frac{1 + \operatorname{erf} S}{2} + \frac{e^{-S^2}}{2\sqrt{\pi}\, S} \right\} \qquad (4.13)$$

Again, these corrections for the two dimensional strip are applied to the proper value for the cylinder. The relevant values of these quantities for the present tests are listed in the brief table.

M	1.96	4.00	5.92
S	1.64	3.34	4.95
S_w	1.17	1.55	1.66
$C_{D,\infty}$(diff.)	3.69	3.06	2.85
$C_{D,\infty}$(spec.)	3.36	2.88	2.76
F	2.46	2.28	2.19
G	1.17	1.50	1.59

TABLE II

FREE MOLECULE FLOW AND NEAR FREE MOLECULE FLOW FUNCTIONS

Both authors have also considered the case of a sphere, and Willis has also considered the case of a circular disk normal to the free stream.

The presence of the $\ln K$ term in the latter result and its absence in the former is not important numerically for the present range of values of S_w; however its basic implication is quite disquieting in that it suggests at least two possibilities: (i) either or both results may be only the leading terms in an actually divergent computation and hence be without any particular significance in themselves, or, alternatively, (ii) the results may be valid only for relatively enormous values of K, say $K \gg 100$.. The $\ln K$ term arises from the two-dimensional character of the strip problem. For another two-dimensional problem, namely linearized Couette flow,[23] Willis has established rigorously the validity of a similar $\ln K$ term, but no such conclusion has been reached for the present case. Neither method, incidentally, leads to $\ln K$ terms for flows with three dimensional symmetry, e.g., flow past a sphere. It is also important to note that terms of $\theta(1/K)$ have been systematically neglicted in Willis's analysis in comparison to the terms of $\theta(\ln K/K)$ which are retained.

Intuitively, the difference in the geometry between a cylinder and a two dimensional strip would not seem to be of major importance. Comparing the axially symmetric analogue -- namely the sphere vs. the disk -- provides some confirmation of this intuitive expectation. For the range of S and S_w of the present tests, Willis's calculations show that the near free molecule correction term for the sphere is about 30% smaller than that for a disk of the same diameter. His calculations indicate a somewhat larger possible dependence on the molecular model used in the strip. The Baker-Charwat results for $M,S \to \infty$ would also be expected to be somewhat questionable at $M \sim 2$, but quite good at $M = 6$.

The comparison between the cylinder drag data and the two dimensional strip theories has been indicated on Figures 4, 5, and 6. The $M = 1.96$ data appears to be in at least marginal agreement with theory. The higher Mach number results, however, seem to be at complete odds with the theoretical predictions. The observed departure from free molecule flow appears to be less than predicted; or, alternatively, the value of K at which a departure from free molecule flow begins to be dectable, i.e., ~ 2-3%, is lower than predicted, namely about 10 instead of the theoretical value of almost 100. It seems unlikely this departure could be due to effects of geometry, molecular model or speed ratio (in the case of the Baker-Charwat theory). In view of the apparent discrepancy, it would appear advisable to continue both theoretical and experimental studies in the "near free molecule flow" regime.

V. CONCLUSIONS

1) Experimental values for the drag coefficient of cross-stream cylinders in supersonic flow have been determined for a particular set of thermal conditions but for Knudsen numbers extending from continuum to free molecule flow.

2) The results are a smooth interpolation between inviscid values at low Knudsen number and free molecule flow predictions for diffuse reflection at high Knudsen number.

3) There seems to be a discrepancy between the experimental values and the theoretical predictions for the near free molecule flow range of high Knudsen number.

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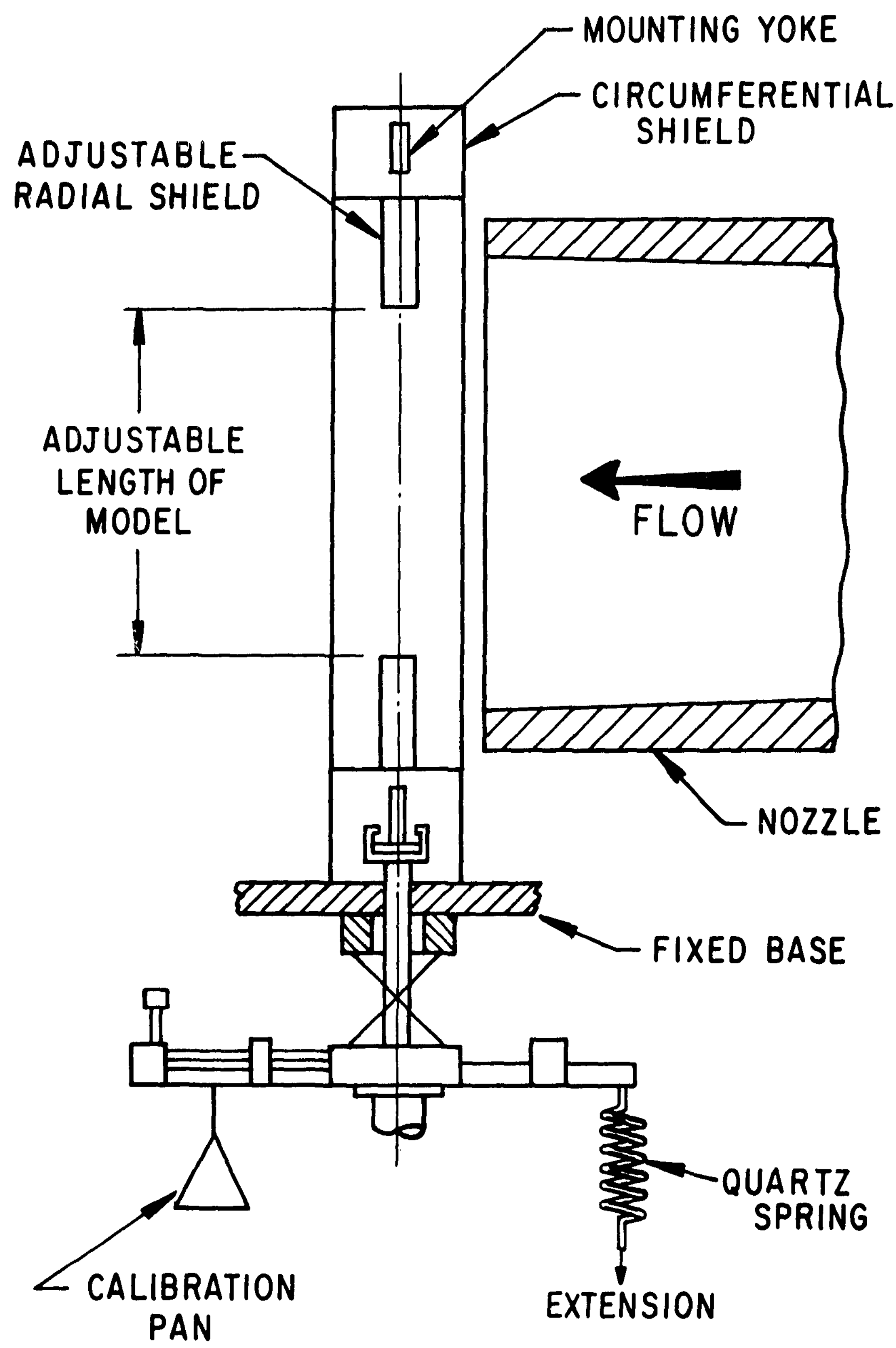

FIG. 1 FORCE MEASUREMENT SCHEMATIC

HYD-7692

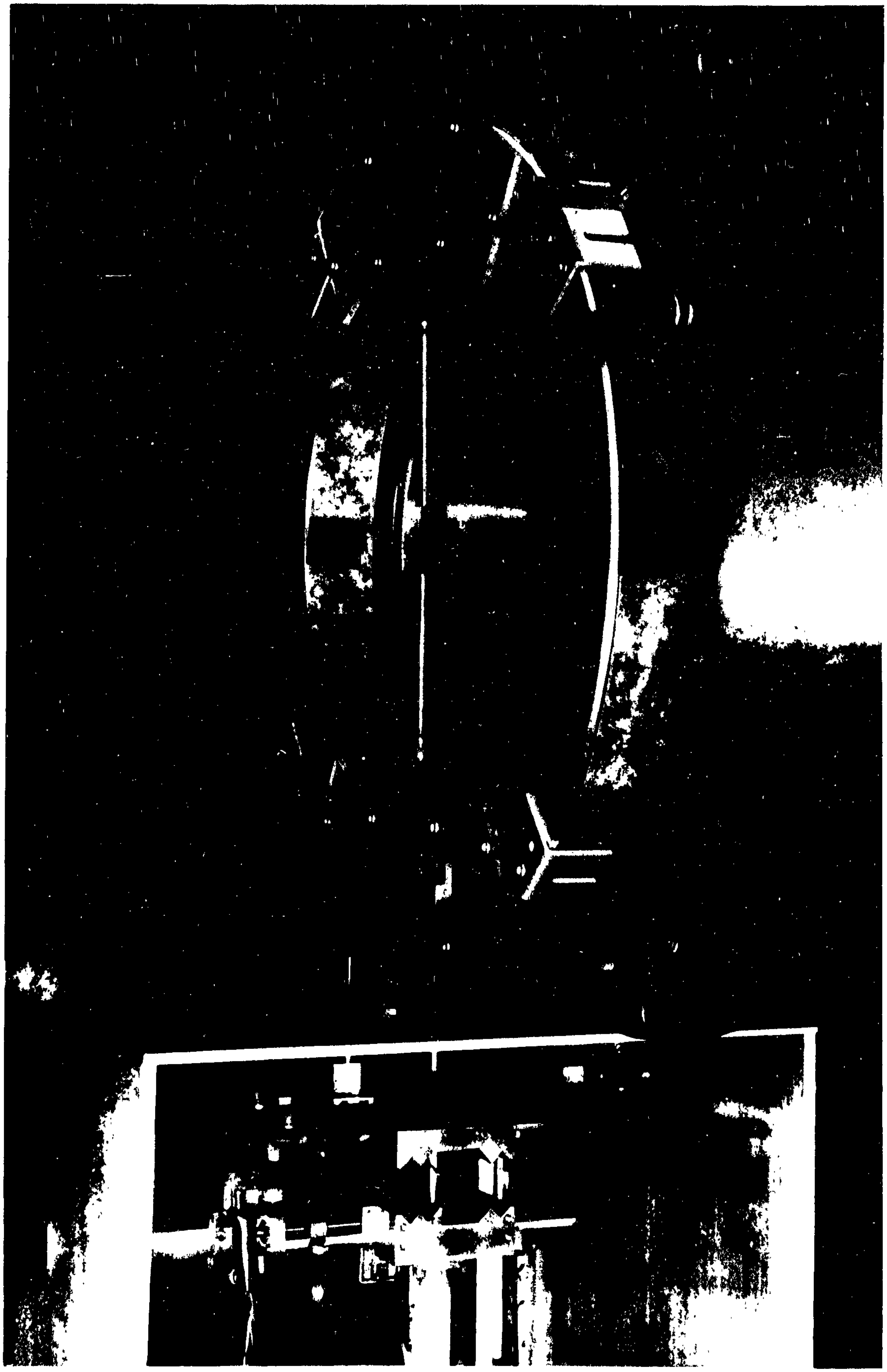

FIGURE 2. MODEL AND BALANCE MOUNTED IN WIND TUNNEL

HYD 7693

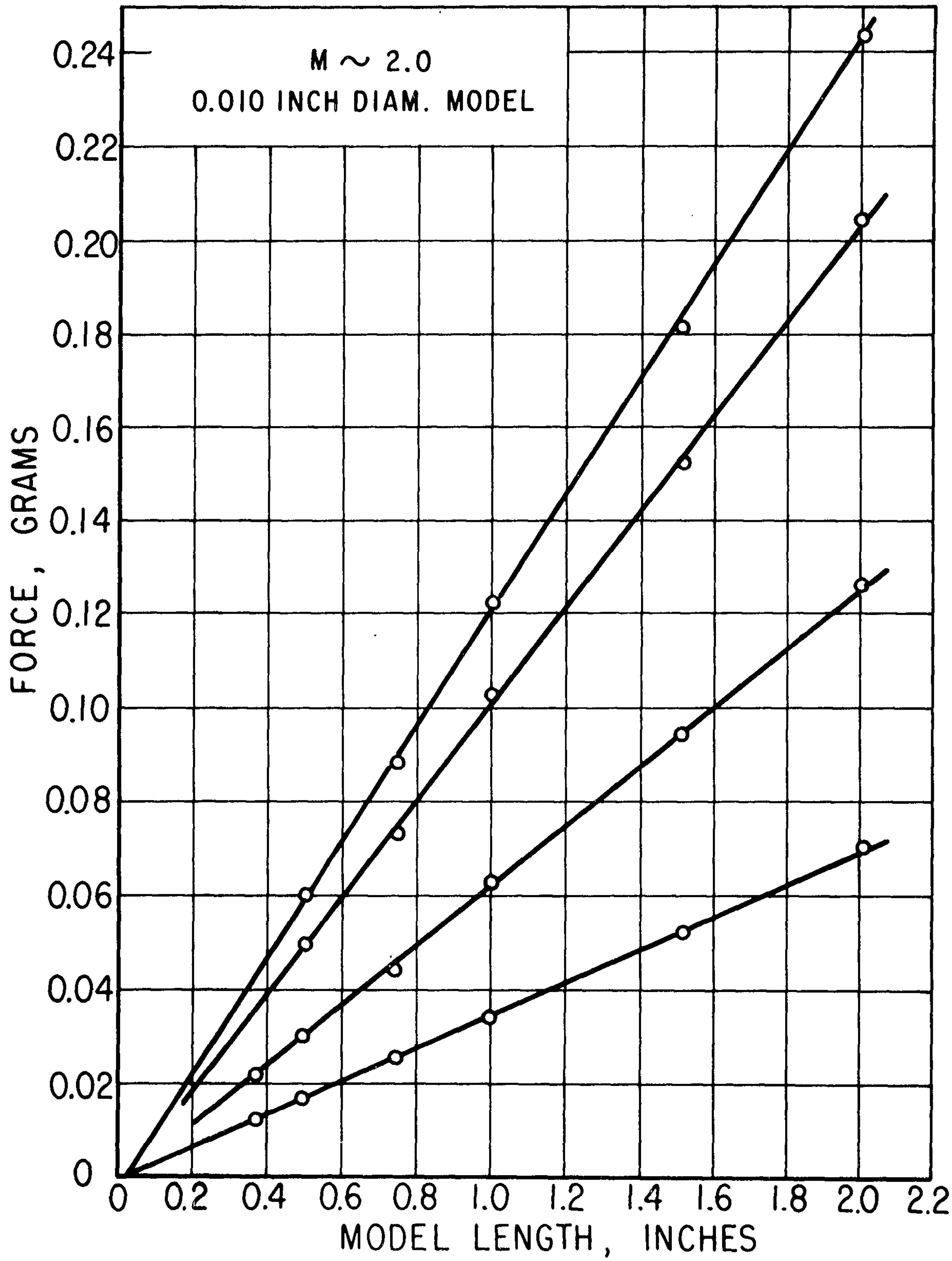

FIG. 3 TYPICAL FORCE - LENGTH RESULTS

HYD-7694

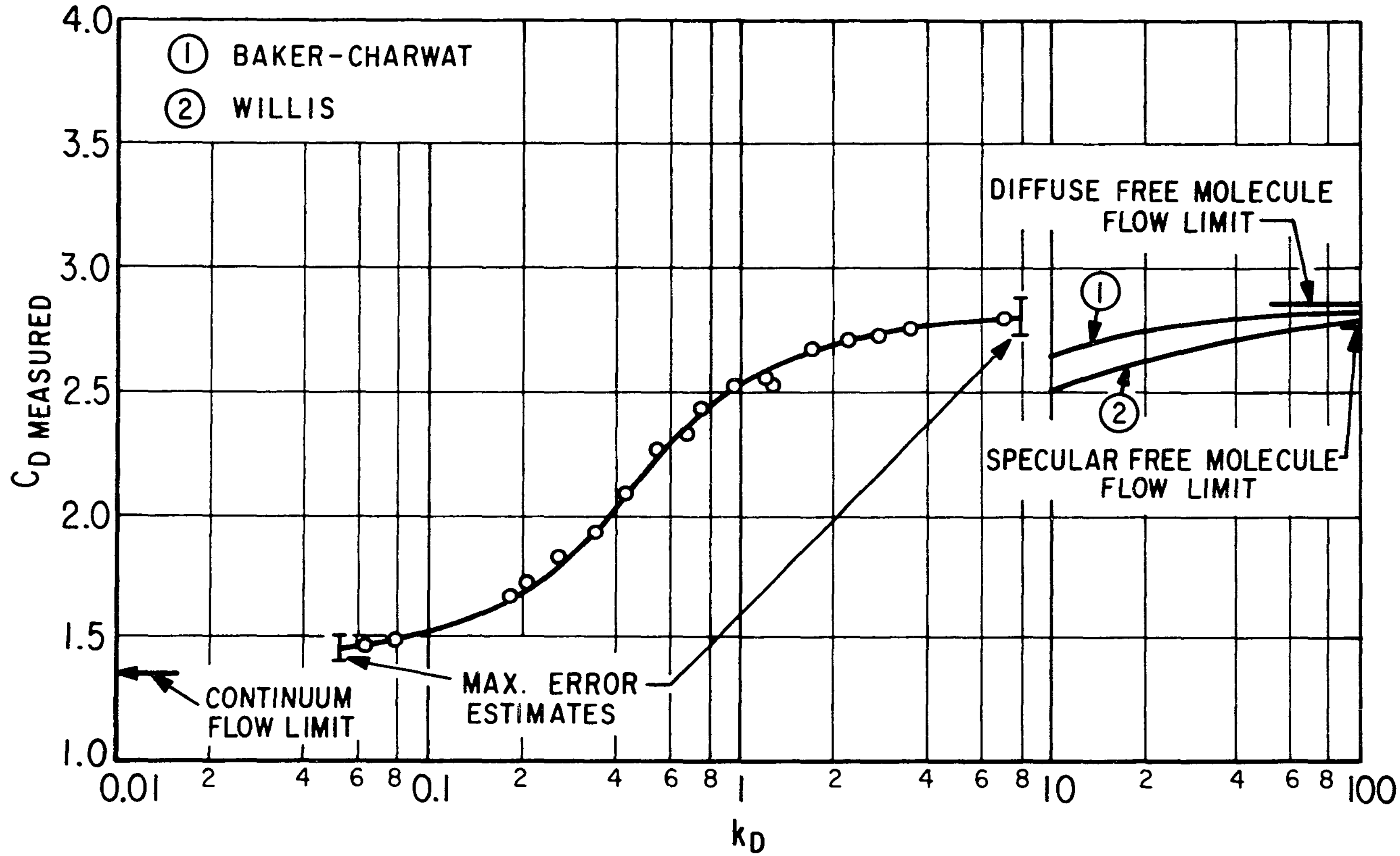

FIG. 4 CYLINDER DRAG AT M = 5.92

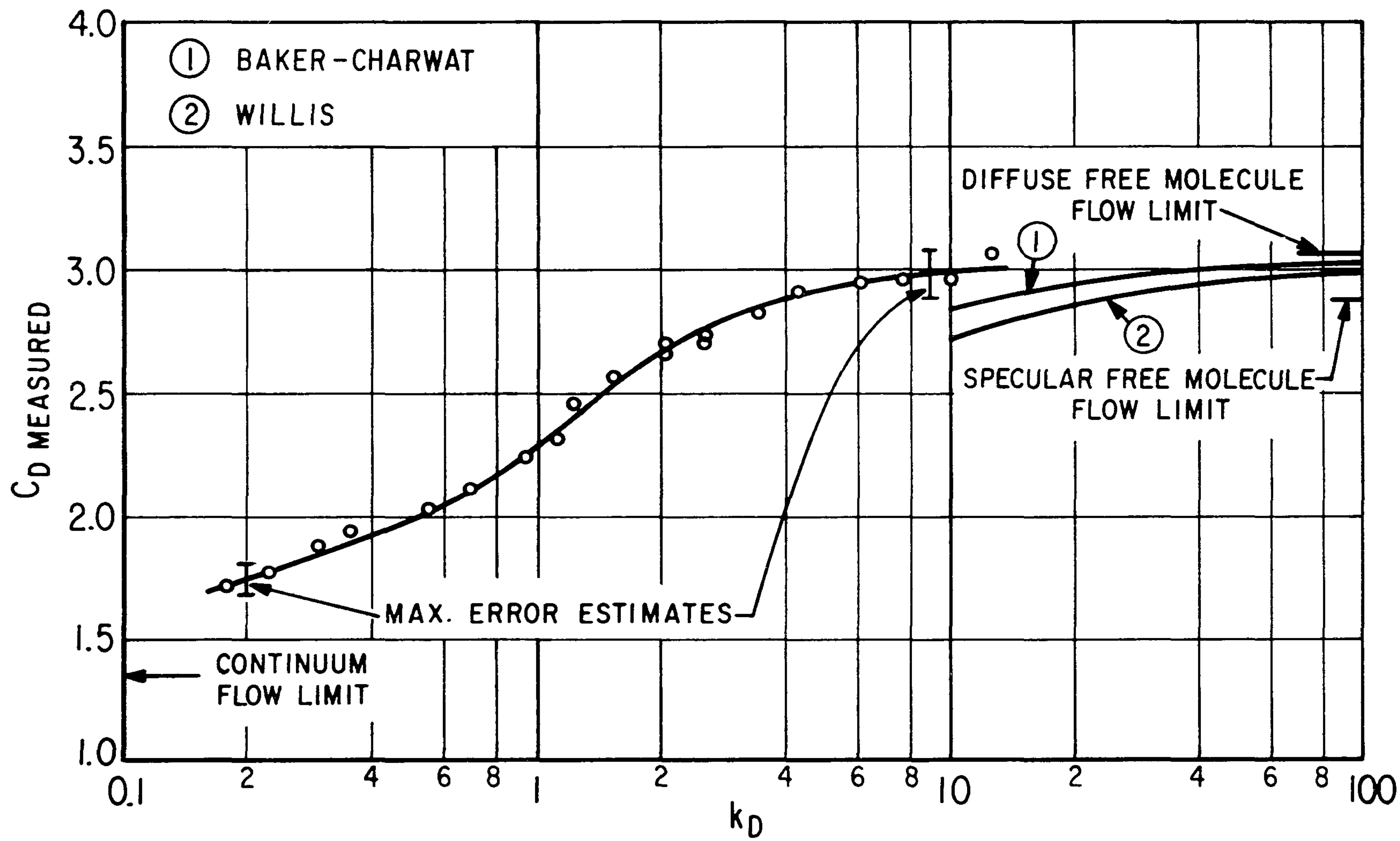

FIG. 5 CYLINDER DRAG AT M = 4.00

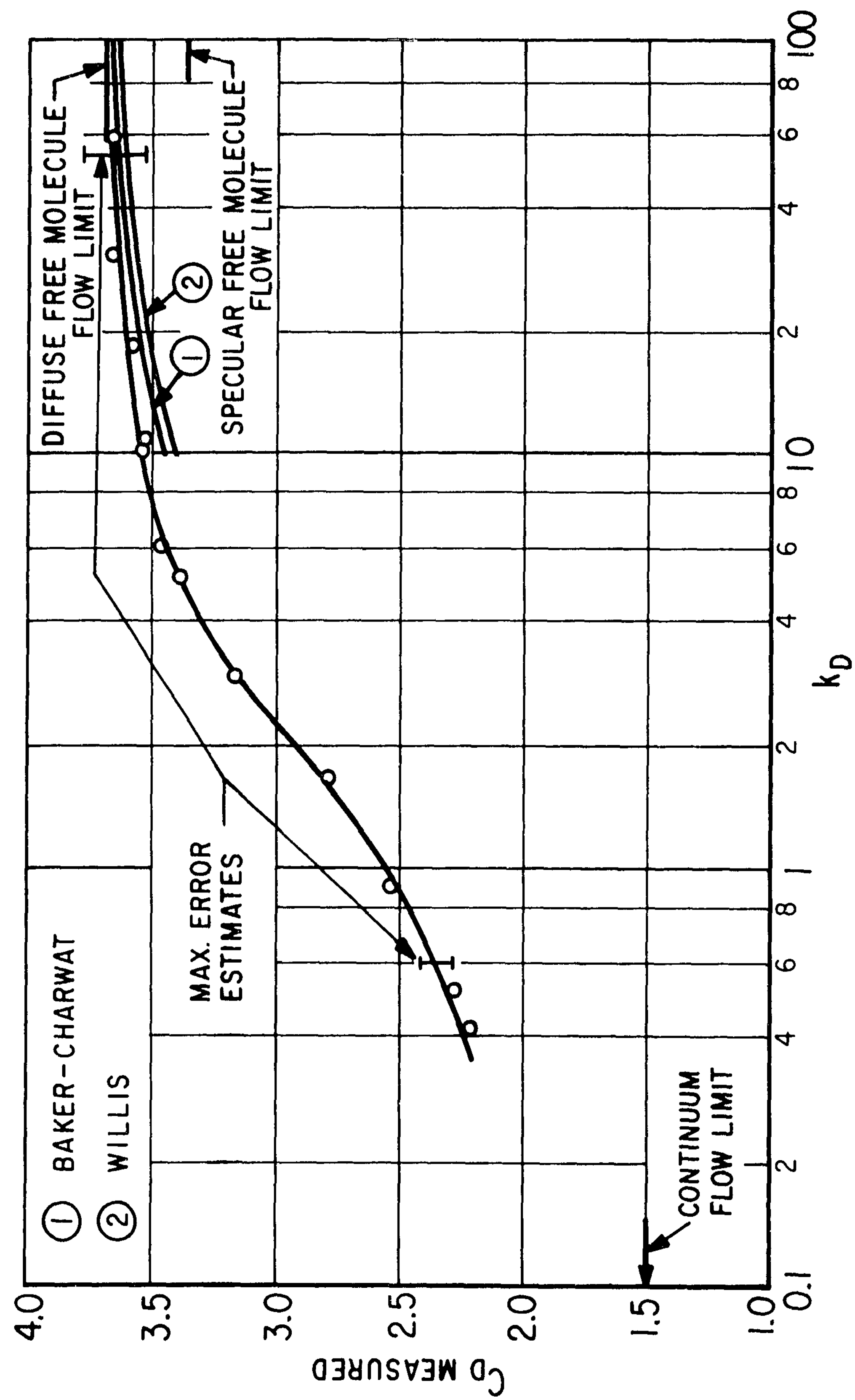

FIG. 6 CYLINDER DRAG AT M = 1.96

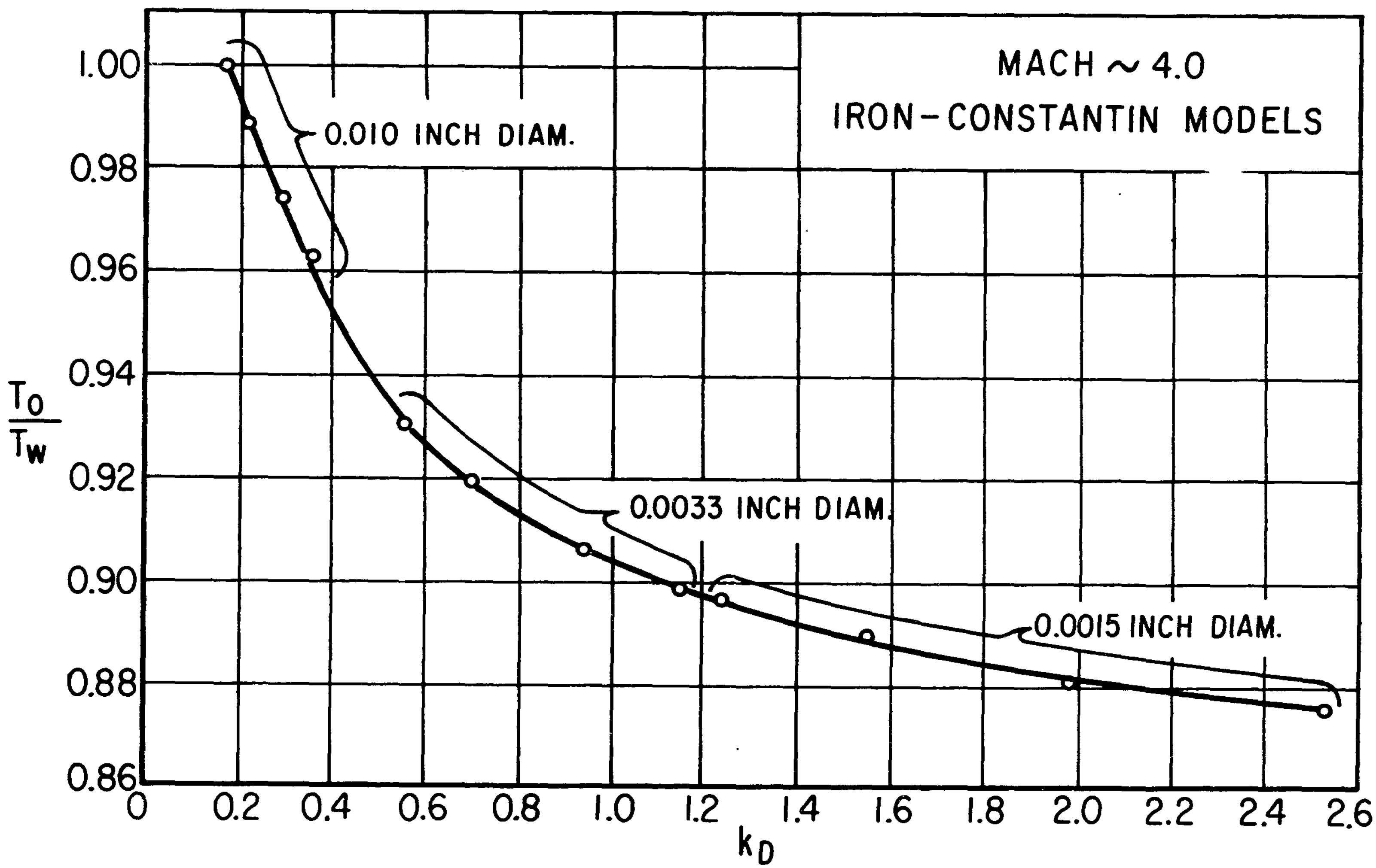

FIG. 7 TYPICAL MODEL TEMPERATURE RESPONSE

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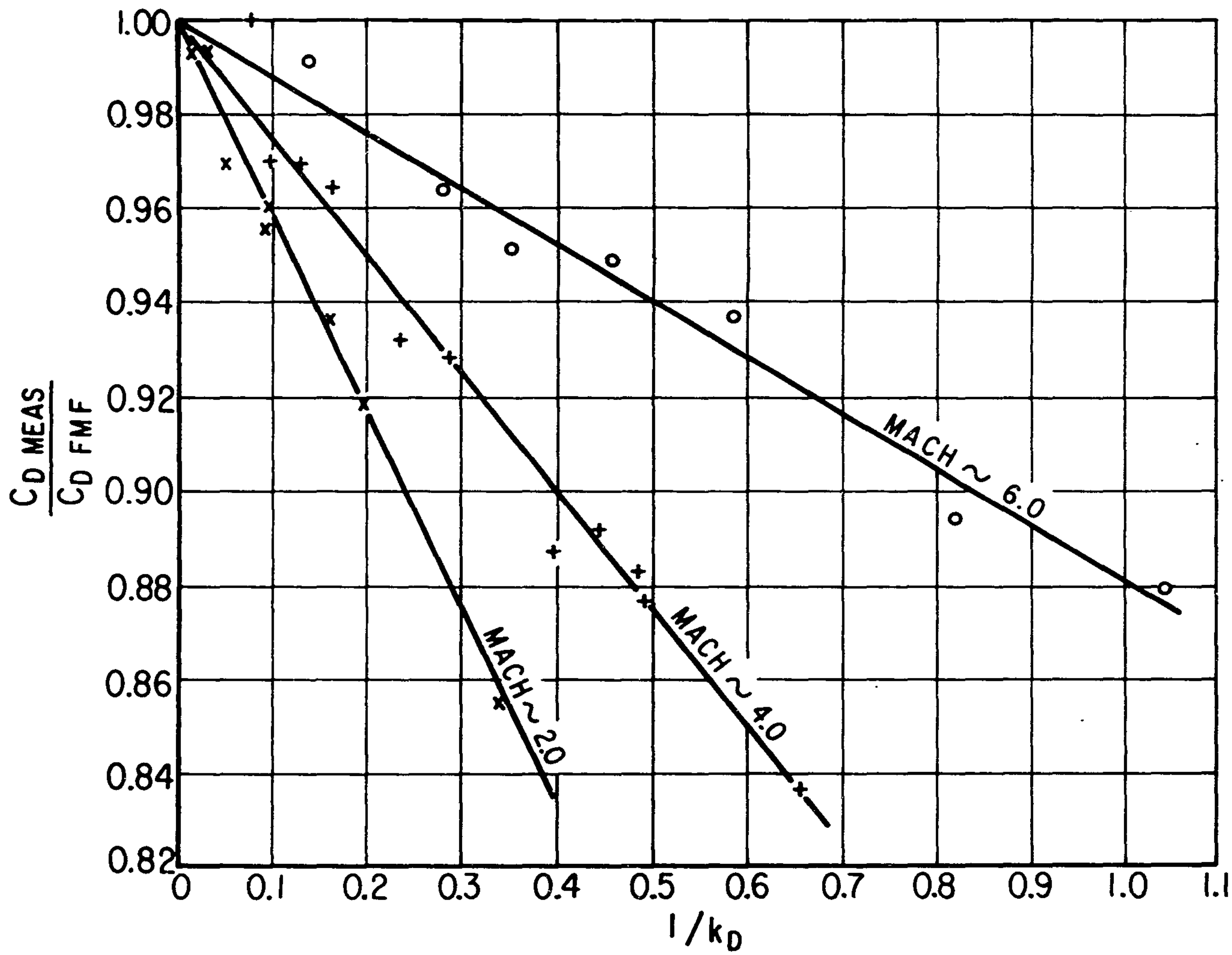

FIG. 8 COMPARISON OF MEASURED VALUES TO COMPUTED LIMITING COEFFICIENTS

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